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HIGH RESOLUTION STUDIES OF SUNSPOTS AND FLUX TUBES

Contract NAS8-39747
Progress Report for 1 November 1993 to 1 February 1994

Introduction and Summary

This contract is for a three-year research study of sunspots and magnetic flux tubes in the solar atmosphere, using tunable filter images collected with a CCD camera during observing runs at the Canary Islands observatories in Spain. The best observations are analyzed and compared with theoretical models, to study the structure and dynamics of sunspots, their connections with surrounding magnetic fields, and the properties and evolution of smaller flux tubes in plage and quiet sun. Scientific results are reported at conferences and published in the appropriate journals. The contract is being performed by the Solar and Astrophysics Laboratory, part of the Lockheed Palo Alto Research Laboratory (LPARL) of the Research and Development Division (RDD) of Lockheed Missiles and Space Co., Inc. (LMSC). The principal investigator is Dr. Alan Title, and the research is done by him and other scientific staff at LPARL and Solar Physics Research Corporation (SPRC), often in collaboration with visiting scientists and students from other institutions.

Highlights during this reporting period include completing the final version of a paper on the Evershed effect, writing a paper on magnetic diffusion, continuing work on contrast of small flux tubes, and work on the development of new models to interpret our sunspots observations.

Major Activities During This Reporting Period

Evershed Effect

Dick Shine completed the final version of a paper on the Evershed effect which is to be published in *Ap.J* in July. A copy of the title page is attached. A contribution entitled ``Dynamics of the Evershed Effect" for the last solar physics NATO workshop (held in November 1993 at Utretch, Holland) was completed. The title page is attached. It is still subject to changes since the editorial process is not complete. The workshop proceedings will appear in the usual book format late this year or early next year.

Dr. Neal Hurlburt has been working on the theoretical interpretation of our sunspots observations. To understand some of the dynamics, he has developed a new MHD convection model in cylindrical coordinates to model fluid motions within the penumbra. The basic numerical algorithms, developed with Lockheed internal funds, uses sixth-order compact finite differences (Lele, S. 1992, J. Comp. Phys. 103,16) for spatial derivatives in radius and depth, a pseudo-spectral representation for azimuthal derivatives, and sixth-order Bulirsch-Stoer method for time advance. Currently a two-dimensional, axisymmetric model is being run and the three-dimensional model without magnetic fields is being tested.

Dr. Ken Topka continued his work on the flux tube study under a subcontract. His progress report is attached.

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Study of Diffusion "Corks"

Alan Title has nearly completed a study of diffusion "corks" (i.e. flux tubes) on the solar surface in collaboration with George Simon and Nigel Weiss. Diffusion coefficients calculated both from observations and the kinematic models are significantly larger than those measured in plage observations and enhanced network. Reasonable estimates of cell sizes and lifetimes yield diffusion coefficients that are close to the 600 km^2/s used by Sheeley and his collaborators in their surface diffusion models. We conclude that: 1) Surface diffusion is reasonable mechanism for dispersing the magnetic outside of plages and enhanced network; 2) The appearance of plages and enhanced network can not be explained by adjustment of the cell sizes or surface velocities; 3) Diffusion is not sufficient to explain the appearance of plages and enhanced network; and 4) Simple models of diffusion with moving stagnation points can explain the functional form of the diffusion coefficients produced from the kinematic models.

Related Activities

Tom Berger, a graduate student working under the direction of Alan Title and Dick Shine and funded by Stanford continued his study of the dynamics of small scale magnetic flux elements in the solar photosphere. Using the Lockheed/Swedish Solar Observatory data collected in the summer of 1993 at La Palma, several time sequences of images taken in the 4304 Angstrom bandhead of the CH radical have been made into movies. These movies show with unprecedented clarity the motion and evolution of magnetic flux tubes on scales below 200 km. Such movies allow detailed observation of the interplay between small flux tubes and larger magnetic structures such as pores and sunspots. These observations will constrain theoretical models of flux tube formation and evolution and may lead to a significant advance in our understanding of solar magnetic activity in general.

Specific tasks accomplished by Mr. Berger over the period were producing two one-hour movie sequences and performing single frame analysis on two frames from 31 August 1993 and 20 September 1993. These analyses resulted in the measurement of 308 and 1225 flux tubes, respectively. Size, aspect ratio, contrast, and location have been measured. A draft paper has been written for submission as a letter to Nature.

Spending Status

At the end of this quarter, approximately 46% of the initial incremental funding was spent (not counting the subcontract) and approximately 46% of the LPARL work planned for the first year was completed. The subcontract commitment represents about 10% of the initial incremental funding; progress on that work is also judged satisfactory. No problems are anticipated at this time in completing the studies for the contract.

Plans for the Period 1 February Through 1 May 1994

1. Continue to review progress with Dr. Topka on the flux tube study.

2. Continue to develop the models for the theoretical interpretations of our sunspot observations.

3. Submit abstracts for the AGU/AAS SPD Meeting in May.

4. Submit the diffusion paper for publication.

5. Plan an observing expedition to La Palma in late May and June.

NATO workshop

N/S

LARGE-SCALE PHOTOSPHERIC MOTIONS: FIRST RESULTS FROM AN EXTRAORDINARY ELEVEN-HOUR GRANULATION OBSERVATION

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Abstract. We present a preliminary report of a unique 11-hr observation of solar granulation obtained at the Swedish Solar Observatory (SSO) on La Palma, Canary Islands, on 5 June 1993. The high quality of the granulation images provided correlation tracking data during every observing minute of this run. A supergranular outflow and a sink (inflow) with associated vorticity lasted for the entire time.

Key words: granulation, mesogranulation, supergranulation, large-scale motions, vortices, outflows, sinks, correlation tracking

1. Introduction

Solar physicists have dreamed for years of obtaining the "perfect" time sequence, one with sub-arcsec seeing that lasts an entire day. Some adverse combination of effects has always thwarted such an observation: seeing that deteriorates too soon, clouds that appear, or instruments that fail. There was great hope that the SOUP experiment on NASA's Spacelab 2 mission in 1985, without atmospheric distortions or clouds, would permit 7 to 10 days of such observations. But instrumental problems ruined this possibility, and SOUP came back with only 27 minutes of white-light data. Nevertheless, much was learned from this short, but eye-opening, sequence. For the first time, correlation tracking (November and Simon, 1988) was used to reveal previously unknown details of several types of large-scale motions at the solar surface. These included outflows and inflows related to supergranules, mesogranules, and motions in an active region (Simon *et al.*, 1988). They served to whet the

DYNAMICS OF THE EVERSHED EFFECT

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Abstract. The dynamics of the Evershed effect are investigated using high resolution movies of sunspots obtained with the Lockheed tunable filter system at the Swedish Solar Observatory on La Palma. We find that the Evershed effect is modulated with a typical period of 10 minutes and is related to outward proper motions seen in both dopplergrams and continuum images that can be tracked over most of the width of the penumbra.

Key words: sunspots, oscillations, magnetic fields

1. Introduction

Since 1987 the Solar Physics Group at Lockheed have been using a sophisicated tunable filter and detector system called the Solar Optical Universal Polarimeter (SOUP) to obtain high resolution movies of the solar photosphere and chromosphere. Solar activity and sunspots have been major objectives and we have obtained many observations for analyzing flows and oscillations in sunspots. Data sets obtained include time series of continuum images, magnetograms, photospheric dopplergrams, H_α images, H_α dopplergrams, and Na I 5896Å dopplergrams. The instrument has been described by Title *et al.* (1992a) and some results on the magnetic geometry of sunspots are given in Title *et al.* (1993). Video movies made from these data have been shown at many meetings and workshops. There are many questions about the structure and dynamics of sunspots that we hope these data will eventually help answer. To date, some of the most interesting results involve the dynamics of the Evershed effect, which is the subject of this paper.

Discovered spectroscopically more than 80 years ago (Evershed, 1909), the Evershed effect is a line shift seen in sunspot penumbrae consistent with a radial outflow. Evershed's early observations established that the velocity was primarily horizontal to the solar surface with little if any vertical or tangential components, and that it ended abruptly at the outer edge of the penumbra. Observations up to about 1965 are covered in Schröter's (1967) comprehensive review. Using high resolution filtergrams, Beckers (1968) showed that the Evershed shift was concentrated in the darker penumbral structures but some high resolution spectroscopic studies failed to show a correlation (e.g., Weihr and Stellmacher, 1989 and Lites, Scharmer, and Skumanich 1990). The recent study by Title *et al.* (1992a) confirms the correlation and

FACULAR CONTRAST AND SMALL MAGNETIC ELEMENTS

PROGRESS REPORT - FEBRUARY 1, 1994

Introduction

The Lockheed tunable filter has been used to observe the Sun each summer since 1988 at the Swedish Solar Observatory, La Palma, Canary Islands. The resulting data sets have high spatial resolution and high photometric accuracy. Also, magnetograms can be co-aligned accurately with images of the photosphere that are taken nearly simultaneously.

Because of the above properties, these data are useful for a variety of measurements, including the intensity of the photospheric footpoints of small magnetic elements in active regions. This is often referred to as facular contrast. Many previous measurements of facular contrast have been published. We believe that the Lockheed - La Palma measurements represent significant improvements over previous measurements. Furthermore, we have extended these measurements to the small magnetic elements that exist outside of active regions, in the quiet sun. These are usually called the quiet sun network, because the action of supergranules sweeps them up to form a lose, network-like structure covering the entire solar surface. Because the magnetogram signals are weak and the footpoints are very faint in quiet sun network, very few measurements of contrast of quiet sun network have ever been published. The Lockheed - La Palma results are the first we are aware of that determine the contrast of the quiet sun network from center to limb.

The measurement of center-to-limb contrast can be used for two distinct and interesting applications. First, it tells us something about the properties of small flux tubes. All physical models must successfully predict the measurements. Second, we can produce the best estimates to date of the effect small magnetic elements have on solar luminosity variations. If the number of small magnetic elements present on the surface of the Sun varies significantly during the 11-year activity cycle, and it appears that it does, then the luminosity of the Sun should vary accordingly. Satellite measurements show a distinct 11-year cycle in total solar irradiance, of magnitude 0.1%, that is in phase with the activity cycle.

Science Results - Pores

A new algorithm has been developed that very carefully identifies all pores in any given observation. The earlier algorithm using a simple threshold proved inadequate. For our best observations at disk center, the darkest pixels in quiet sun intergranular lanes have contrast of -22% or less, while the the brightest pixels in pores are -12% or more. This means that there exists no simple threshold that can effectively eliminate all pores, while including all intergranular lanes. Both conditions are required for accurate photometric results.

All of our earlier active region photometry is still significantly contaminated by pores. This means that the intensity of the solar surface in active region plage is not as dark as was measured. Fortunately, the error is slight for the results already published. This is because contrasts were published in the range 200 G to 600 G, where contamination due to pores (which have very high magnetic signals) is slight. Our estimates of the systematic error in measured contrasts vary from 0% at 200 G or less, to 5% at 400 G, to more than 40% at 1200 G. The new algorithm will allow us to make a more precise measurement of the contribution that small magnetic elements make to solar variability.

Interestingly, the new pore mask can be used to study the observational properties of pores. For example, the smallest pores we can identify in our data have apparent sizes of 1.2 sq arc second. The observed mean intensity decreases and mean field strength increases approximately linearly with the log of the pore area.

Science Results - Micropores

Starting with the computer program described above, we have developed and applied a new algorithm that identifies micropores present in active region observations. The idea is to locate, count, and measure some of their observed properties. The attempt, while not entirely successful, did lead to some interesting results. For example, in our best data at disk center we find that there are more than 10 micropores for every pore present. The actual count was 29 pores and 318 micropores. The mean observed size is 0.7 sq arc second. The mean observed contrast varies from -1% for the smallest (0.2 sq arc second) to -5% for the largest (4 sq arc second).

The largest micropores found have areas exceeding 4 sq arc second. This is much larger than the smallest pores. When compared to pores, we find that their average filling factor is only 70%. This makes it likely that many of these micropores are not individual flux tubes, but instead are composites of two or more smaller flux tubes.

In many cases there is no physical isolation between pores and active region plage. Pores tend to be embedded in, and surrounded by plage, even at the limits of our highest resolution observations. Pores lack a "moat" usually seen around sunspots. Except for occasional moving magnetic elements the moat is free from magnetic elements. Also, micropores preferentially exist near the edges of pores. This suggests that fragmentation of pores may represent an important source of micropores.

It is important to understand the properties of micropores because they comprise about 50% of the magnetic flux contained in active region plage. As such they are a major contributor to solar irradiance variations.

Science Results - Bright Points

Observations made at La Palma in 1993, using a 5 Å wide filter centered in the G-band (4304 Å), have produced exciting new results on the motion and evolution of bright points. This work has been done largely by Dr. Alan Title of Lockheed and Stanford University graduate student Tom Berger. Individual frames are diffraction-limited (resolution about 0.2 arc sec), and the bright points show typical contrasts of +30% or more. In one of the best frames, centered on active region plage, these scientists counted over 1200 bright points.

However, diffraction-limited images made at 5000 Å and 6000Å show no such features. Their limiting resolution is only slightly poorer, and cannot account for the difference. Certainly the bright points must be present, but it is apparent that their contrast is much lower. We have constructed a model that explains this difference. If correct, the model reveals interesting new details of the vertical structure of these small flux tubes. This model is easily testable, with new data obtained at La Palma in 1994.

Further, we have tested the hypothesis that a cluster of bright points can appear like a micropore in our 6000 Å data. In general, comparison of our model to the data shows clearly that most micropores cannot be a simple cluster of bright points, unless significant "interaction" occurs. What this means is that when 2 or more bright points come in close physical proximity they must turn dark. The G-band results mentioned above seems to eliminate this possibility.

Models of Active Region Plage

A new model (or simulation) of active region plage has been developed using Monte Carlo techniques. It is used to predict contrast as a function of magnetogram signal at disk center, and can be compared directly with observations of the same type. The new feature of this model is that a large number of flux tubes with a wide range of diameters can be simulated simultaneously.

The model can produce good agreement with the observations only when a wide range of flux tube diameters are included. The range must include both bright and dark structures (bright points and micropores). Again, the existence of micropores is demanded unless a cluster of bright points can turn dark. Such interaction seems to be precluded observationally, as discussed above. The "knee" seen in the observations (where the slope of contrast versus magnetogram signal changes abruptly) is predicted in the models, and is due to the existence of, and an upper limit to the size of, bright points. Further, the model shows that the larger the mean diameter of the bright points, the lower the total relative flux of active region plage that is permitted to be composed of bright points. For example, if the mean diameter of bright points is 0.3″, then AR plage can contain no more than 15% (by magnetic flux) bright points. If the mean diameter of bright points is only 0.1″, however, then AR plage can contain up to 85% bright points.